US006935355B2

(12) **United States Patent**
Eldridge

(10) **Patent No.: US 6,935,355 B2**
(45) **Date of Patent: Aug. 30, 2005**

(54) **SMALL SCALE ACTUATORS AND METHODS FOR THEIR FORMATION AND USE**

(75) Inventor: **Jerome M. Eldridge**, City of Los Gatos, CA (US)

(73) Assignee: **Micron Technology, Inc.**, Boise, ID (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **10/320,901**

(22) Filed: **Dec. 16, 2002**

(65) **Prior Publication Data**

US 2003/0089865 A1 May 15, 2003

Related U.S. Application Data

(62) Division of application No. 09/644,365, filed on Aug. 23, 2000, now Pat. No. 6,581,479.

(51) **Int. Cl.**[7] **F16K 31/00**

(52) **U.S. Cl.** **137/1**; 251/11; 251/62; 251/89

(58) **Field of Search** 251/11, 62, 89; 60/527, 528; 310/306, 307; 137/67, 72, 74, 341, 828, 833, 1; 417/92, 99

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,945,504	A	*	7/1960	Bredtschneider et al.	251/89
3,256,686	A	*	6/1966	Lindberg	60/516
4,377,209	A		3/1983	Golben	
5,731,797	A		3/1998	Akiyama et al.	

(Continued)

FOREIGN PATENT DOCUMENTS

DE	19749011 A1	*	5/1998	A61M/5/168

OTHER PUBLICATIONS

U.S. Appl. No. 60/114,203.*
U.S. Appl. No. 09/258,363, Forbes et al., filed Feb. 26, 1999.
U.S. Appl. No. 09/546,084, Eldridge, filed Apr. 10, 2000.
U.S. Appl. No. 09/773,522, Farrar et al., filed Feb. 20, 2001.
Case Western Reserve University, R. Quinn, Biologically Inspired Robotics Laboratory, 2 pages, http://biorobots.cwru.edu/, Jun. 6, 2002; "Micro–Cricket Series Robots," 2 pages, http://biorobots.cwru.edu/projects/c__mrobot/c__mrobot.htm, Jun. 6, 2002; Bio–Robotics Lab Publications, 4 pages, http://biorobots.cwru.edu/publications/publicat.htm, Jun. 6, 2002.
E.A. Avallone and T. Baumeister III, "Marks' Standard Handbook for Mechanical Engineers," 10th Ed., Section 3.3 "Mechanics of Fluids by J.W. Murdock," McGraw Hill, (1996), pp. 3–29—3–61.
V.J. Minkiewicz, J. Stasiak, J.O. Moore, R. Eaton and J.M. Eldridge, "Some Properties of a–Si_xC_{1-x}:H Films Prepared by a Mixed Frequency PECVD Process," 1992 Materials Research Society Symposium Proceedings, San Francisco, California, vol. 268, pp. 133–138.

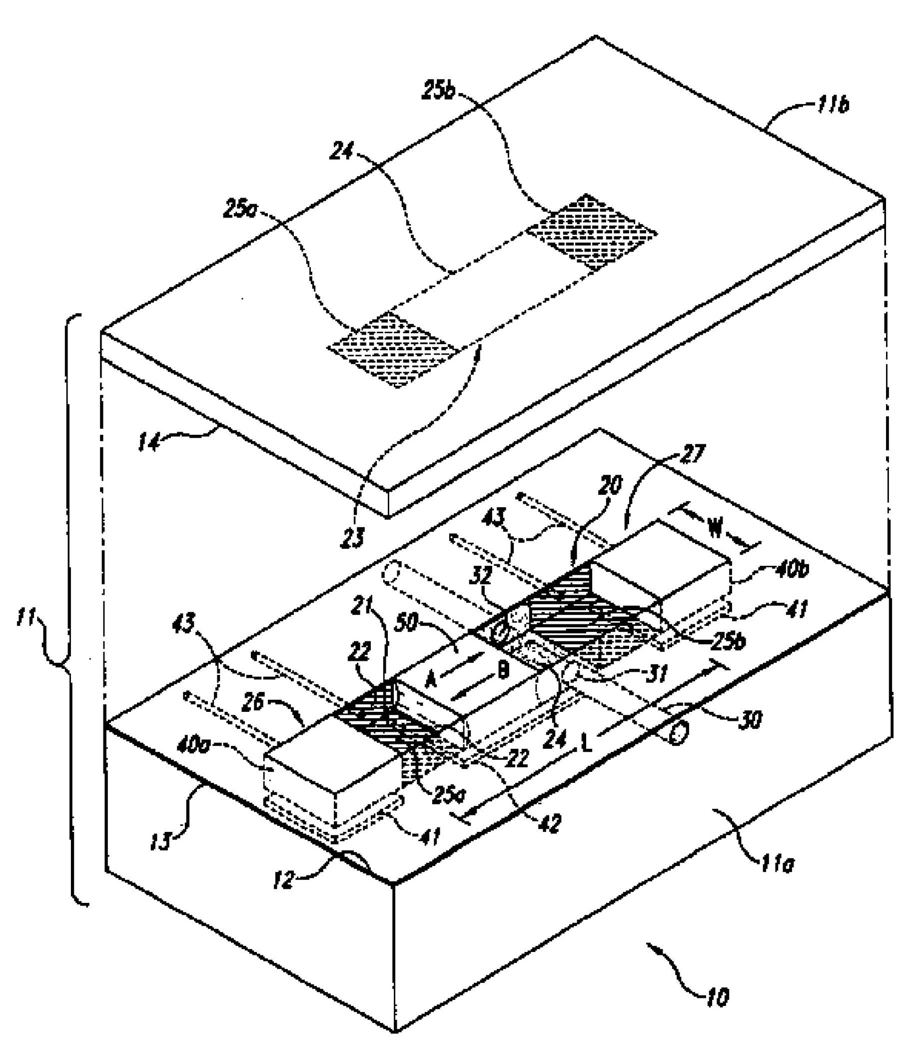
(Continued)

Primary Examiner—Eric Keasel
(74) *Attorney, Agent, or Firm*—Perkins Coie LLP

(57) **ABSTRACT**

An actuator assembly and method for making and using an actuator assembly. In one embodiment, the assembly includes an actuator body having an actuator channel with a first region and a second region. An actuator is disposed in the actuator channel and is movable when in a flowable state between a first position and a second position. A heater is positioned proximate to the actuator channel to heat the actuator from a solid state to a flowable state. A source of gas or other propellant is positioned proximate to the actuator channel to drive the actuator from the first position to the second position. The actuator has a higher surface tension when engaged with the second region of the channel than when engaged with the first region. Accordingly, the actuator can halt upon reaching the second region of the channel due to the increased surface tension between the actuator and the second region of the channel.

22 Claims, 5 Drawing Sheets



U.S. PATENT DOCUMENTS

5,738,658	A		4/1998	Maus et al.	
5,810,325	A		9/1998	Carr	
5,847,280	A	*	12/1998	Sherman et al.	73/514.32
5,871,342	A		2/1999	Harte et al.	
5,959,338	A		9/1999	Youngner et al.	
5,997,527	A		12/1999	Gumucio et al.	
6,023,121	A	*	2/2000	Dhuler et al.	310/307
6,102,897	A	*	8/2000	Lang	251/11 X
6,241,480	B1	*	6/2001	Chu et al.	417/99
6,288,437	B1		9/2001	Forbes et al.	
6,367,251	B1	*	4/2002	Wood	60/528
6,435,396	B1		8/2002	Eldridge	

OTHER PUBLICATIONS

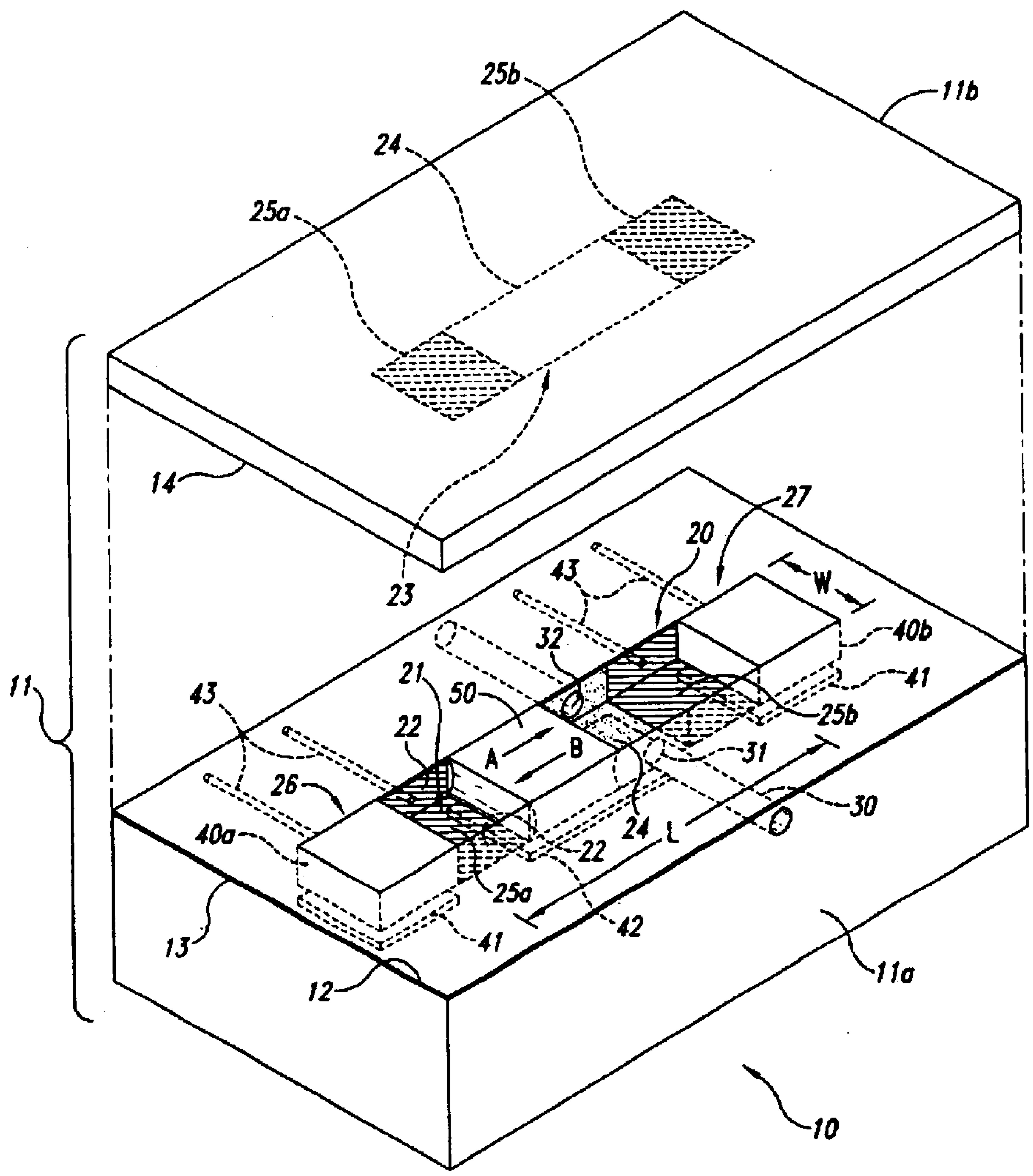
S. Dushman and J.M. Lafferty, Revised by David G. Worden, "Flow of Gases Through Tubes and Orifices," Scientific Foundations of Vacuum Technique, John Wiley & Sons, Inc., New York, Second Edition, Chapter 2, (1962), pp. 80–117.

S. Dushman and J.M. Lafferty, Revised by Francis J. Norton, "Gases and Metals," Scientific Foundations of Vacuum Technique, John Wiley & Sons, New York, Second Edition, Chapter 8, (1962), pp. 516–559.

Fraunhofer ISE, Public Relations, Fuel Cell Supplies Electricity for Laptop, "Banded–Structure Membrane Fuel Cell and Hydrogen Storage in a Hydribe," http://www.ise.fhg.de/Products/brennstoffzelle.html Jun. 6, 2002, 3 pages.

JMC (USA), Inc., Hydrogen Storage Alloy Applications, "Hydrogen Storage Alloys for Nickel–Metal Hydride Batteries," http://www.jmcusa.com/mh2.html, Jun. 6, 2002, 4 pages.

* cited by examiner



25b
11b
24
25a
14
23
27
20
43
W
40b
32
41
11
43
21
50
25b
22
A
B
31
26
30
24
L
40a
22
25a
42
13
41
12
11a
10

Fig. 1

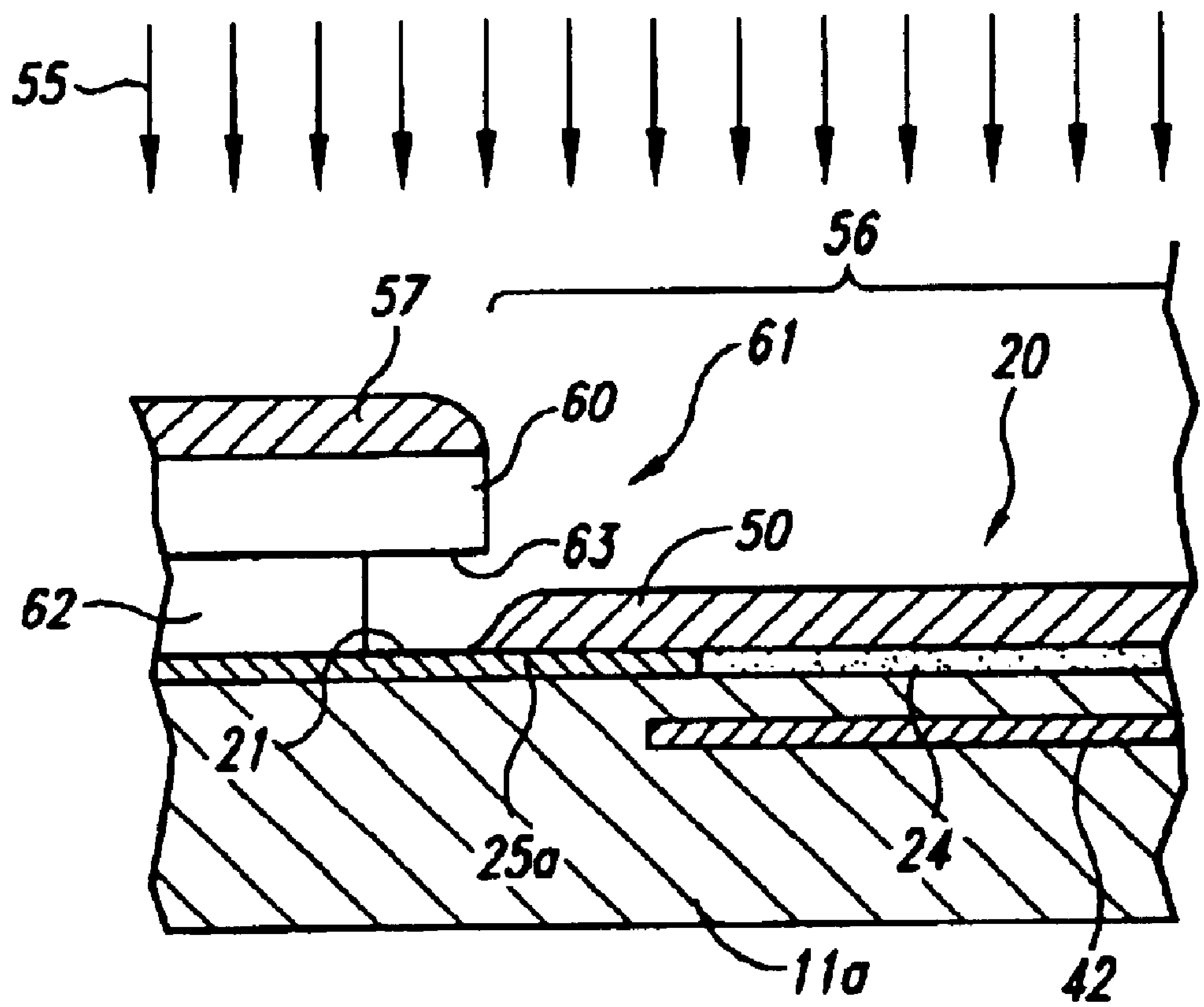


Fig. 2

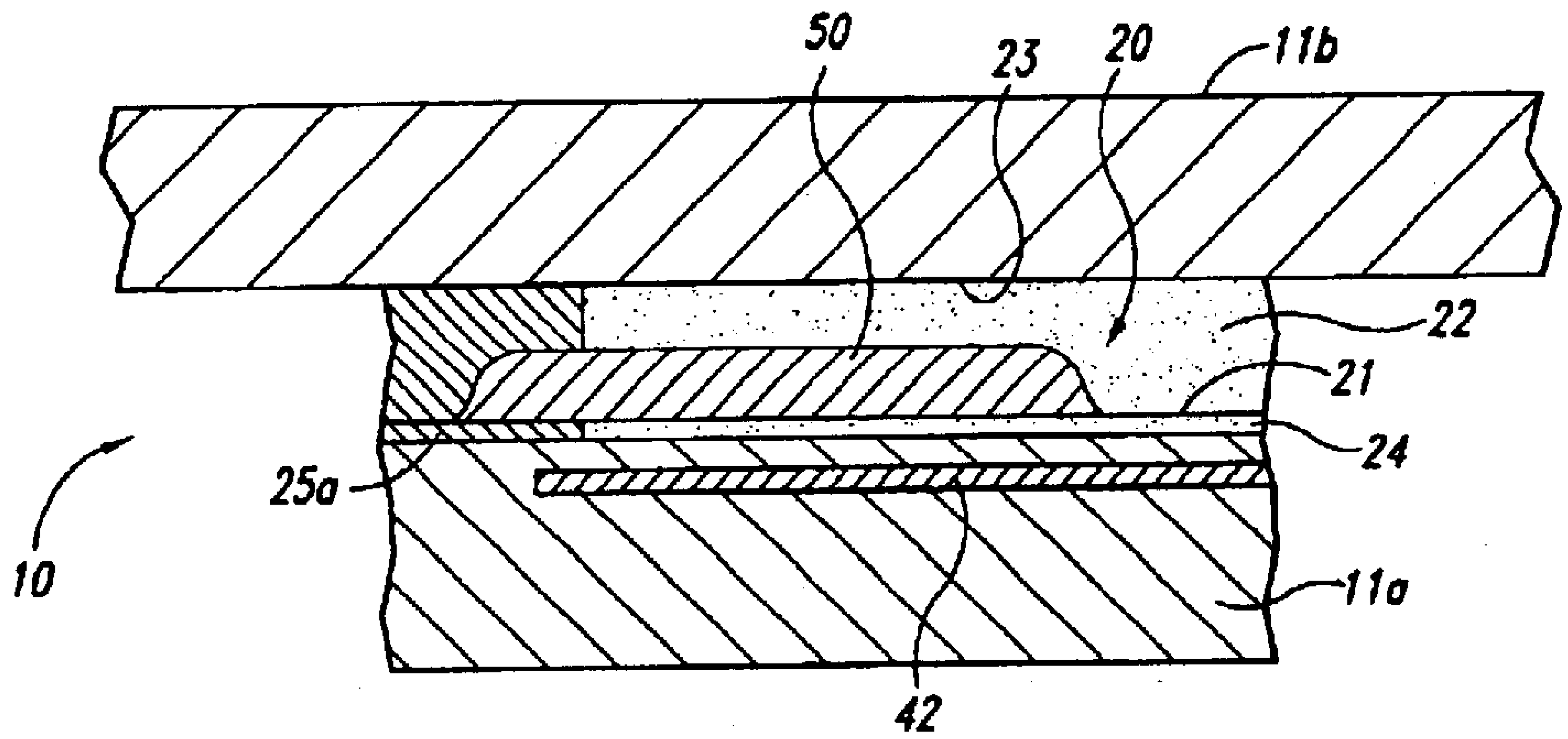


Fig. 3A

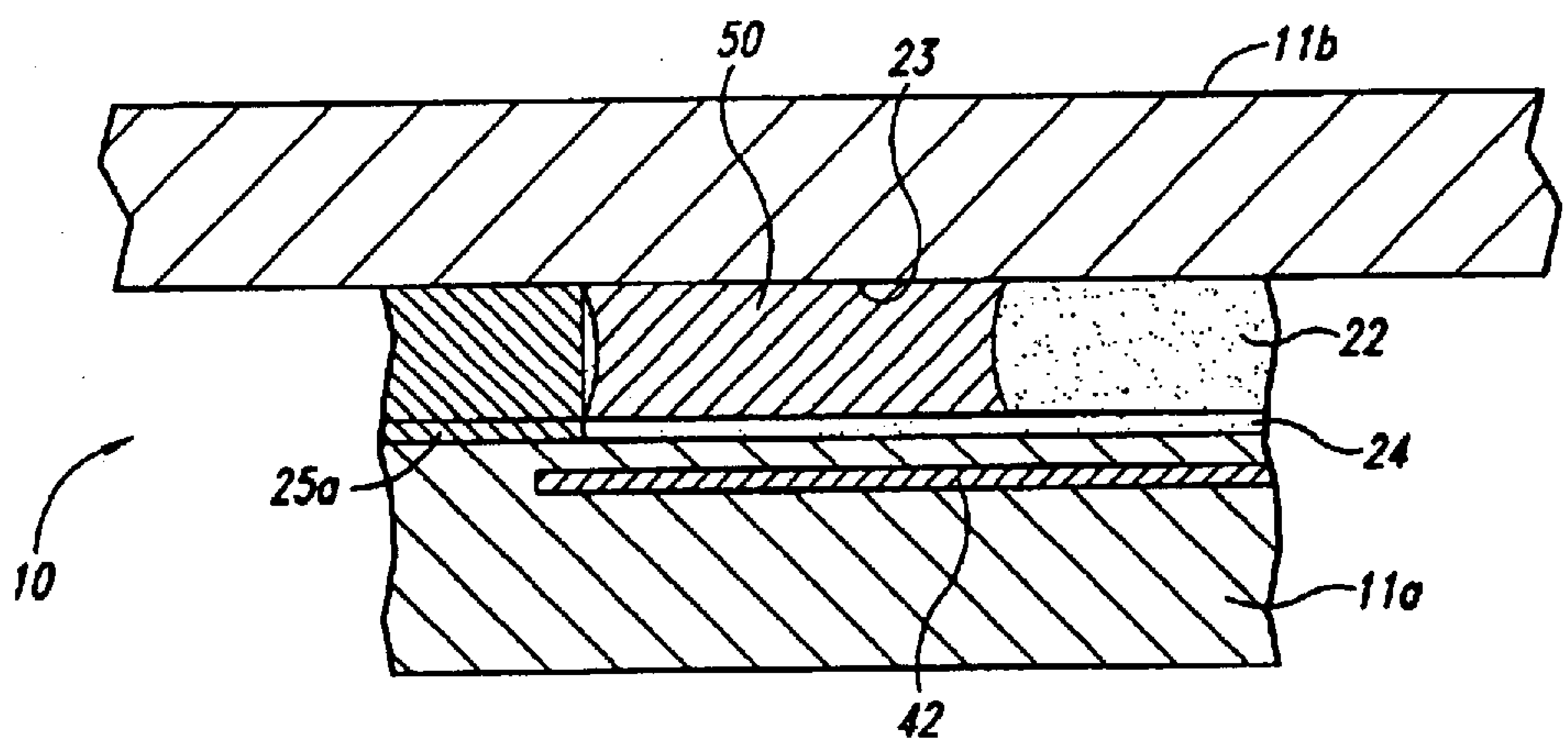


Fig. 3B

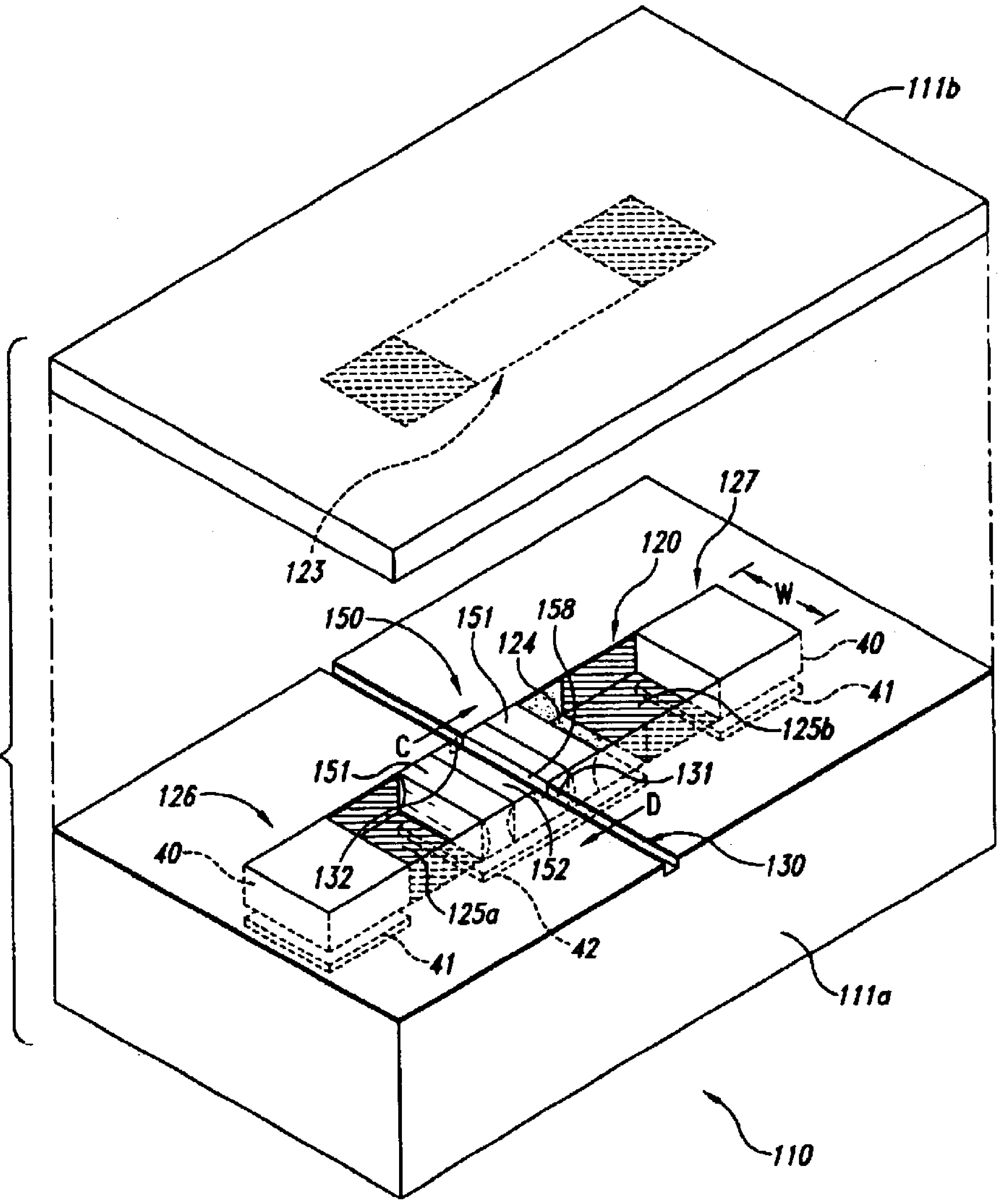

111b
123
127
120
W
150
151
158
124
40
41
125b
111
C
151
131
126
D
40
132
152
130
125a
42
41
111a
110

Fig. 4

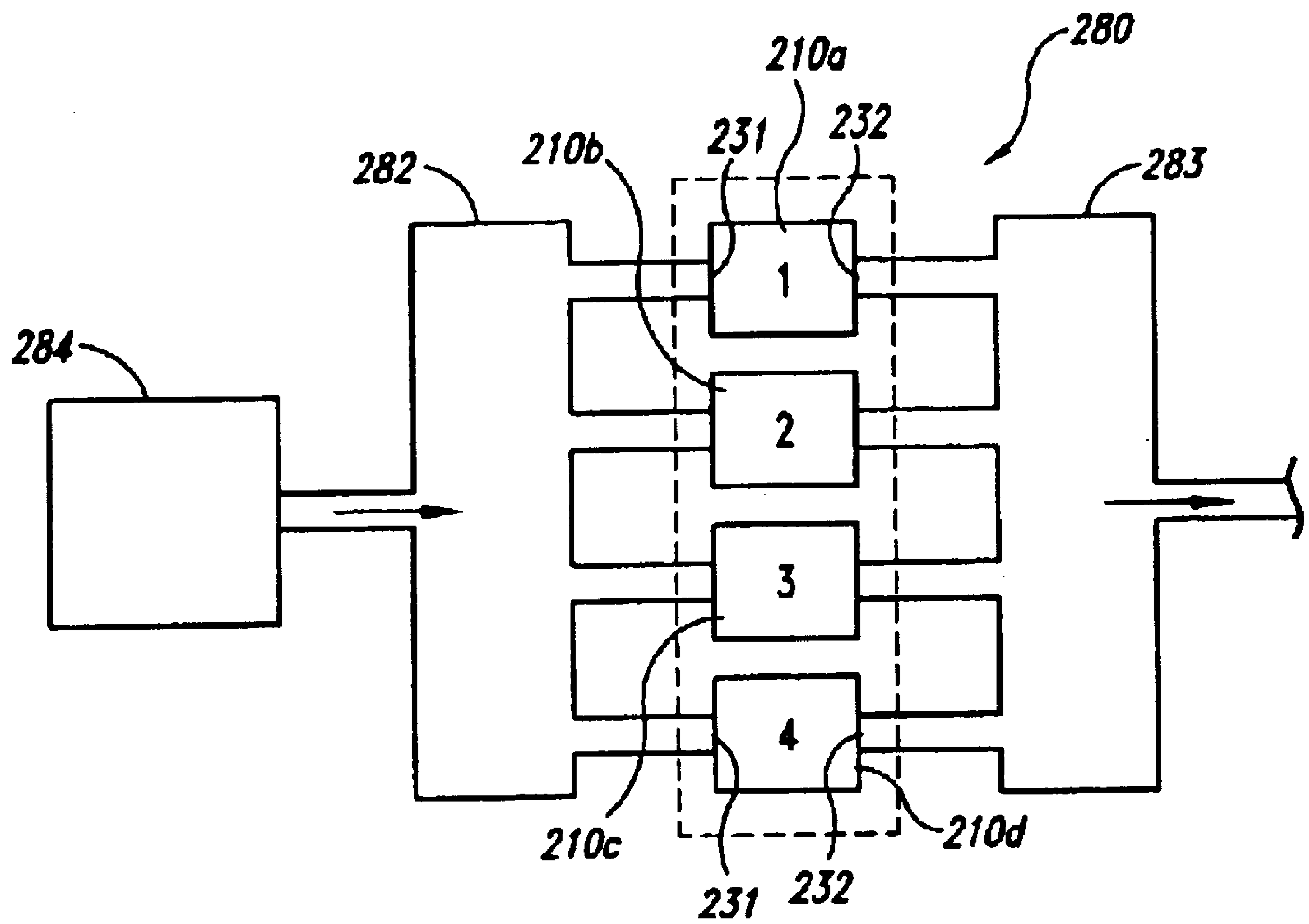


Fig. 5

SMALL SCALE ACTUATORS AND METHODS FOR THEIR FORMATION AND USE

CROSS REFERENCE TO RELATED APPLICATION

This application is a divisional of U.S. patent application Ser. No. 09/644,365 now U.S. Pat. No. 6,581,479, filed on Aug. 23, 2000.

TECHNICAL FIELD

The present invention is directed toward small actuators for devices such as valves, and methods for forming and using such actuators.

BACKGROUND

Microvalves are miniature valves used to control fluid flows at low flow rates. Such valves and other microelectromechanical (MEMS) devices are conventionally used in several industrial and professional applications where it is important to precisely regulate the flow of small quantities of gases or liquids. For example, microvalves are used for some types of medical research (such as DNA research), medical treatments, and other types of applications that involve metering fluids at low flow rates.

Some conventional microvalves are formed directly in a semiconductor substrate (such as silicon) using techniques generally similar to those used to form integrated circuits. Such valves typically include a flexible diaphragm that opens and closes a fluid orifice when selected voltages are applied to the valve. Examples of such valves are disclosed in U.S. Pat. No. 5,810,325 to Carr, which is incorporated herein in its entirety by reference.

One drawback with some conventional diaphragm microvalves of the type described above is that the valves may fail because the diaphragm can fracture or deform after repeated uses. Another drawback is that conventional diaphragms typically do not exert a large sealing force to close the fluid orifice. Accordingly, such diaphragms may not be suitable for valves that regulate high pressure fluids.

SUMMARY

The present invention is directed toward actuators and methods for forming and using actuators. An actuator assembly in accordance with one aspect of the invention includes an actuator body having an actuator channel with a first end and a second end spaced apart from the first end. An actuator is disposed in the actuator channel and is movable when in a flowable state from a first position in the actuator channel to a second position in the actuator channel. Accordingly, the assembly can further include a heater positioned proximate to the actuator channel to heat the actuator from a solid state to a flowable state. In a further aspect of the invention, the actuator body can include a fluid passageway having an orifice in fluid communication with the actuator channel. Accordingly, the actuator can allow fluid to flow through the orifice when the actuator is in the first position and block the flow of fluid through the orifice when in the second position.

The invention is also directed toward a method for manufacturing an actuator. In one aspect of the invention, the method can include forming a channel in a substrate, positioning an actuator in the channel with the actuator being movable within the channel between a first position and a second position when the actuator is in a flowable state, and disposing an actuator heater adjacent to the channel with the actuator heater configured to at least partially liquify the actuator. The method can further include forming the channel to have a first region and at least one second region adjacent to the first region. The first region can have a first surface characteristic, and the second region can have a second surface characteristic different than the first surface characteristic. The actuator can have a first surface tension when in a flowable state and contacting the first region, and the actuator can have a second surface tension when in a flowable state and contacting the second region. The second surface tension can be greater than the first surface tension such that the actuator can halt its movement through the channel upon contacting the second region.

The invention is also directed toward a method for controlling an actuator. The method can include heating the actuator in an actuator channel from a solid state to a flowable state, moving the actuator in a first region of the actuator channel from a first position to a second position, and cooling the actuator to solidify the actuator in a second position. The method can further include halting the motion of the flowable actuator at the second position by engaging the actuator with a surface of a second region of the channel. For example, the actuator can have a surface tension when in contact with the second region that is higher than a surface tension of the actuator when in contact with the first region such that the actuator can halt its movement in the channel upon contacting the second region.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a partially exploded top isometric view of an actuator assembly in accordance with an embodiment of the invention.

FIG. **2** is a cross-sectional side view illustrating a process for depositing an actuator on a portion of the assembly shown in FIG. **1** in accordance with an embodiment of the invention.

FIGS. **3A–3B** are cross-sectional side views illustrating additional processes for forming the actuator shown in FIG. **2** in accordance with an embodiment of the invention.

FIG. **4** is a top isometric view of a portion of an assembly having an actuator with a slider portion in accordance with another embodiment of the invention.

FIG. **5** is a partially schematic view of a valve assembly in accordance with yet another embodiment of the invention.

DETAILED DESCRIPTION

The present disclosure describes actuators, such as valve actuators, and methods for making and using such actuators. Many specific details of certain embodiments of the invention are set forth in the following description and in FIGS. **1–5** to provide a thorough understanding of these embodiments. One skilled in the art, however, will understand that the present invention may have additional embodiments, or that the invention may be practiced without several of the details described below.

FIG. **1** is a partially exploded top isometric view of an actuator assembly **10** formed in accordance with an embodiment of the invention. In one aspect of this embodiment, the assembly **10** is configured to regulate a flow of fluid (liquid, gas or another flowable substance) through a fluid passageway **30**. Accordingly, the assembly **10** can include a body **11** having a first portion **11***a* that houses the fluid passageway **30** and a second portion **11***b* attached to the first portion **11***a*.

The first portion **11***a* can include an actuator or piston **50** that slides within an actuator channel or piston channel **20** to either open or close a segment of the fluid passageway **30**.

In one embodiment, the body **11** can be formed from a semiconductor material, such as silicon. Accordingly, the features formed in the body **11** can be formed using techniques generally similar to those conventionally used for forming integrated circuits in semiconductor substrates, as described in greater detail below. In other embodiments, the body **11** can be formed from non-semiconductor materials and/or with other techniques. In either embodiment, many of the features of the body **11** can be formed separately in the first portion **11***a* and the second portion **11***b*. The portions **11***a*, **11***b* can subsequently be joined by attaching an upper surface **12** of the first portion **11***a* to a lower surface **14** of the second portion **11***b*. Accordingly, the first portion **11***a* can include a bonding layer **13** to promote adhesion between the first portion **11***a* and the second portion **11***b*. Alternatively, the second portion **11***b* can include a bonding layer in addition to or in lieu of the bonding layer on the first portion **11***a*, or the bonding layer **13** can be eliminated.

In one embodiment, the channel **20** in the body **11** can include a bottom surface **21** and opposing side surfaces **22** in the first portion **11***a*, and a top surface **23** in the second portion **11***b*. Accordingly, the channel **20** can be completely enclosed when the second portion **11***b* is joined to the first portion **11***a*. In one aspect of this embodiment, the side is surfaces **22** can be perpendicular to the bottom surface **21**. Alternatively, the side surfaces **22** can be canted relative to the bottom surface **21**. In either embodiment, the channel **20** can have a first unwetted region **25***a* (shown by left cross-hatching) toward a first end **26** of the channel **20**, a second unwetted region **25***b* (shown by right cross-hatching) toward a second end **27** of the channel **20**, and a wetted region **24** between the first and second unwetted regions **25***a*, **25***b*. The fluid passageway **30** intersects the channel **20** in the wetted region **24**. Accordingly, the fluid passageway **30** can have an entrance orifice **31** in one side surface **22** of the channel **20** and an exit orifice **32** in the opposite side surface **22**.

The actuator **50** is positioned in the wetted region **24** proximate to the entrance orifice **31** and the exit orifice **32**. When the actuator **50** is in a liquid state (or another flowable state), it can wet and seal against the bottom surface **21**, the side surfaces **22** and the top surface **23** of the channel **20**. The actuator **50** can also move back and forth along the wetted region **24**, as indicated by arrows "A" and "B," when in the flowable state to close and open the entrance orifice **31**.

In a further aspect of this embodiment, the actuator **50** will not move into either of the unwetted regions **25***a*, **25***b* due to high capillary forces associated with the interface between the actuator **50** and the unwetted regions **25***a*, **25***b*. Accordingly, the motion of the actuator **50** can be limited to linear travel between a first position and a second position. In the first or open position (shown in FIG. **1**), the actuator **50** is spaced apart from the entrance orifice **31** and the exit orifice **32** of the fluid passageway **30** to allow fluid to pass through the fluid passageway **30** from the entrance orifice **31** across the channel **20** to the exit orifice **32**. In the second or closed position, the actuator **50** is positioned between the entrance orifice **31** and the exit orifice **32** to block the flow of fluid through the fluid passageway **30** beyond the entrance orifice **31**.

In one aspect of an embodiment of the assembly **10** shown in FIG. **1**, the actuator **50** can be moved back and forth within the channel **20** by sequentially introducing a gas toward one of the first end **26** or the second end **27** of the channel **20**. For example, the assembly **10** can include two gas sources **40** shown in FIG. **1** as a first gas source **40***a* toward the first end **26** and a second gas source **40***b* toward the second end **27**. In a further aspect of this embodiment, each gas source **40** can include a metal hydride that releases hydrogen when heated and reabsorbs the hydrogen when cooled. Accordingly, the first gas source **40***a* can be heated to release hydrogen into the channel **20** toward the first end **26** and drive the actuator **50** toward the closed position, as indicated by arrow A. Alternatively, the second gas source **40***b* can be heated to release hydrogen toward the second end **27** of the channel **20** and drive the actuator **50** toward the open position, as indicated by arrow B. Additional materials relating to metal hydrides and other gas-containing metals are included in Chapter **8** of "Scientific Foundations of Vacuum Technique," by S. Dushman and J. M. Latterly (1962), and in pending U.S. patent application Ser. Nos. 09/546,084 and 09/258,363, all incorporated herein in their entirety by reference.

In one embodiment, the body **11** can include vent channels **43** coupled to the gas sources **40** and/or the channel **20**. The vent channels **43** can provide a safety outlet for hydrogen at the gas source **40** and/or in the channel **20** to vent the hydrogen if the pressure of the hydrogen exceeds a preselected value. The vent channels **43** can also dampen pressure pulses produced by the gas sources **40** by receiving some of the gas released by the gas sources **40**. Alternatively, the vent channels **43** can release the hydrogen produced by the gas sources **40** from the assembly **10** during normal operation. Accordingly, the hydrogen is not reabsorbed by the gas sources **40**. In a further aspect of this alternate embodiment, the gas sources **40** can be used for a limited number of actuator movements, or the gas sources **40** can be replenished with gas from an external source.

In yet another aspect of an embodiment of the assembly **10** shown in FIG. **1**, the body **11** can include one or more heaters for controlling the temperature of the gas sources **40** and/or the actuator **50**. For example, the body **11** can include gas source heaters **41** adjacent to and thermally coupled to each of the gas sources **40** to independently heat the gas sources **40** and release the hydrogen (or other gas) from the gas sources **40**. The body **11** can further include an actuator heater **42** positioned adjacent to and thermally coupled to the wetted region **24** of the channel **20** to heat and at least partially liquify the actuator **50** prior to moving the actuator **50** within the channel **20**. The heaters can be independently controlled to achieve the temperature necessary to release gas from the gas sources **40** and at least partially liquify the actuator **50** at selected phases during the operation of the assembly **10**, as will be described in greater detail below. The heaters can be positioned in the first portion **11***a* of the body **11** (as shown in FIG. **1**) or alternatively, the heaters can be positioned in the second portion **11***b*.

The materials forming channel **20** and the actuator **50** can be selected to enhance the performance of the actuator **50** in the channel **20**. For example, the wetted region **24** of the channel **20** can include a coating of a noble metal (such as platinum or gold), or another metal (such a palladium or rhodium) that resists corrosion and/or is easily wetted by the actuator **50** when the actuator **50** is in an at least partially flowable state. The actuator **50** can accordingly include a material that has a relatively low melting point and that readily wets the wetted region **24**. Suitable materials for the actuator **50** include lead and lead alloys (such as are found in solders), bismuth, cadmium, selenium, thallium, tin and/or zinc. In other embodiments, the actuator **50** can include other metals, alloys, inorganic and/or organic materials, so long as the actuator **50** can achieve an at least partially flowable state when heated and/or can be halted by contact with the non-wetted regions **25***a*, **25***b*. Conversely, the non-wetted regions **25***a*, **25***b* of the channel **20** can be coated with a material that is not easily wetted by the actuator **50**. For example, when the actuator **50** includes lead or a lead alloy, the non-wetted regions **25***a*, **25***b* can include an oxide or a nitride, such as silicon dioxide, aluminum oxide, or silicon nitride. In any of these embodiments, the materials selected for the body **11**, the wetted region **24** and the non-wetted regions **25** have a higher melting point than the material selected for the actuator **50** so that only the actuator **50** will melt when the actuator heater **42** is activated.

In operation, the fluid passageway **30** is coupled to a source of fluid (not shown in FIG. **1**). The actuator heater **42** is activated to at least partially melt the actuator **50** and/or otherwise increase the flowability of at least the external surfaces of the actuator **50** while the actuator **50** remains sealably engaged with the surfaces of the channel **20**. The first gas source **40***a* is activated (for example, by activating the adjacent gas source heater **41**) to release gas into the channel **20** toward the first end **26** and drive the actuator **50** from its first or open position (shown in FIG. **1**) to its second or closed position between the entrance orifice **31** and the exit orifice **32** of the fluid passageway **30**. The actuator **50** halts when it reaches the second unwetted region **25***b*, due to very strong capillary forces at the interface between the actuator **50** and the second unwetted region **25***b*. The actuator heater **42** is then deactivated to solidify the actuator **50** in its closed position with the actuator **50** sealed against the surfaces **21**, **22** and **23** of the channel **20**. The gas source heater **41** is then deactivated and the first gas source **41***a* re-absorbs the released gas.

To open the fluid passageway **30**, the actuator **50** is heated as described above and the second gas source **40***b* is activated to drive the actuator **50** from the closed position to the open position. The actuator **50** is then allowed to cool to solidify the actuator **50** in the open position and seal the actuator **50** against the surfaces of the channel **20**. The second gas source **40***b* is cooled to allow the gas released into the channel **20** to reabsorb to the second gas sources **40***b*. In one embodiment, the foregoing steps can be repeated to cycle the actuator **50** back and forth between the open position and the closed position at a frequency of up to at least 1,000 cycles per second. In other embodiments, the actuator **50** can be cycled at other frequencies higher or lower than 1,000 cycles per second.

In one embodiment, the assembly **10** can be formed in silicon or another semiconductor substrate using photolithographic masking and etching techniques to define several features of the assembly **10**. For example, when the gas source heaters **41** and the actuator heater **42** include electrical resistance heaters, the heaters **41**, **42** can be formed directly in the first portion **11***a* by first etching cavities to accommodate the heaters and then depositing or otherwise disposing in the cavities a conductive material that achieves the desired temperature when an electrical current is applied to the conductive material. Alternatively, the heaters **41** and **42** can be positioned in the second portion **11***b* using similar techniques.

The channel **20** can also be formed in the first portion **11***a* using an etching technique. In one embodiment, the bottom surface **21** and the side surfaces **22** of the channel **20** (including the wetted region **24** and the non-wetted regions **25***a* and **25***b*) can then be oxidized. Next, the wetted region **24** can be coated with a metal adhesion layer, such as chromium, followed by a noble metal film, such as platinum, or another wettable metal material. The top surface **23** of the channel **20** (in the second portion **11***b*) can be processed in a generally similar manner.

Before the second portion **11***b* is attached to the first portion **11***a*, the actuator **50** is positioned in the wetted region **24** of the channel **20**. In one embodiment, the volume of material forming the actuator **50** is selected to span the channel **20** from one side surface **22** to the other and from the bottom surface **21** to the top surface **23** when the body second portion **11***b* is attached to the first portion **11***a*. However, the volume of actuator material does not occupy the entire wetted region **24** to allow for movement of the actuator **50** back and forth between the open and closed positions. When the gas sources **40** include metal hydrides, they can be deposited directly in the ends **26** and **27** of the channel **20**. Alternatively, the hydride or other gas source **40** can be pre-formed and positioned in the channel **20**. The second portion **11***b* of the body **11** can then be attached to the first portion **11***a* in an inert or a reducing environment to promote adhesion between the two portions.

In one embodiment, the actuator **50** can be disposed in the channel **20** using a conventional etch and photomask process. For example, the material forming the actuator **50** can be deposited directly into the channel **20** (and, in one embodiment, over other parts of the first portion **11***a*). A layer of photoresist material can be applied to the actuator material and a positive or negative mask can be used to eliminate the photoresist from all regions except a region that defines the outline of the actuator **50**. The remaining photoresist shields the portion of the actuator material that defines the actuator **50** and the excess actuator material is etched away using conventional etchants.

FIG. **2** illustrates an alternate method for disposing the actuator **50** in the channel **20** in accordance with another embodiment of the invention. This method may be suitable where it is difficult to remove the excess actuator material with an etching process. In one aspect of this embodiment, a spacer layer **62** and a resist layer **60** are disposed on the bottom surface **21** of the channel **20** and on other parts of the first portion **11***a*. An aperture **61** is formed in the resist layer **60** and the spacer layer **62** and is aligned with an actuator deposition region **56** in the channel **20**. The spacer layer **62** can be undercut (for example, by etching the spacer layer **62**) so that the resist layer **60** has an overhanging portion **63** that faces directly toward the bottom surface **21** of the channel **20**. The actuator material **55** is deposited on the first portion **11***a* to form the actuator **50** in the actuator deposition region **56** and an excess portion **57** of the actuator material **55** on the resist layer **60**. The excess portion **57** and the resist layer **60** are then removed by dissolving the spacer layer **62** with an appropriate solvent. The overhanging portion **63** can reduce the likelihood for "bridging" between the actuator **50** and spacer layer **62**, and can also provide an access channel for the solvent.

FIG. 3A is a cross-sectional side view of a portion of the assembly **10** described above with reference to FIG. **1** immediately after attaching the second portion **11***b* to the first portion **11***a*. In one aspect of this embodiment, the actuator **50** is initially disposed in the actuator channel **20** in a solid state to extend over a portion of the wetted region **24** and the first unwetted region **25***a*. The actuator **50** projects upwardly from the bottom surface **21** of the channel **20**, but does not initially contact the top surface **23**. When an electrical current is applied to the actuator heater **42**, the actuator **50** liquifies. Because the surface tension between the liquified actuator **50** and the first unwetted region **25***a* is substantially higher than between the liquified actuator **50** and the wetted region **24**, the actuator **50** retracts from the unwetted region **25***a* to form a meniscus at the interface between the wetted region **24** and the unwetted region **25***a*, as shown in FIG. **3**B. In a further aspect of this embodiment, the liquified actuator **50** wicks upwardly along the side surfaces **22** of the channel **20** to engage the top surface **23**. Accordingly, the actuator **50** can fill the entire cross-sectional flow area of the channel **20** (as shown in FIG. **1**) after its initial liquifaction. When the actuator **50** cools and solidifies, it can form a sealed interface with the surfaces of the channel **20** to prevent fluid in the fluid passageway **30** (FIG. **1**) from escaping past the actuator **50** toward the ends **26**, **27** (FIG. **1**) of the channel **20**. In one embodiment, the actuator **50** can have a length approximately equal to twice its height, and in other embodiments, the actuator **50** can have other dimensions, depending on the dimensions of the channel **20**.

In still further embodiments, the actuator **50** can be disposed in the channel **20** in other manners. For example, the actuator **50** can initially be positioned to reside entirely within the wetted region **24**, rather than extending into the first unwetted region **25***a*. The actuator **50** then wicks up the side surfaces **22** to the top surface **23** of the channel upon being heated, as described above. Alternatively, the actuator **50** can be initially disposed in the channel **20** in a liquid form, provided that the environment in which the assembly **10** is formed has a temperature above the melting point of the actuator **50**.

One feature of an embodiment of the assembly **10** described above with reference to FIGS. **1**–**3** is that the channel **20** and the actuator **50** can be made extremely compact by forming these and other elements of the assembly **10** directly in the body **11**. Accordingly, the overall dimensions of the assembly **10** can be suitable for many subminiature applications. For example, (referring now to FIG. **1**) the channel **20** can have a width "W" of from about one micron to about five microns and a length "L" of from about two microns to about 50 microns. In other embodiments, the dimensions of the channel **20** can be smaller, provided that the techniques for forming the channel **20** and other components of the assembly **10** are compatible with the reduced dimensions. Conversely, the channel **20** and the actuator **50** can be larger in still further embodiments provided that (a) the actuator **50** can remain in contact with the surfaces **21**, **22**, and **23** of the channel **20** when in a liquid state, and (b) the actuator **50** does not develop so much momentum as it moves within the channel **20** that it crosses from the wetted region **24** into either of the unwetted regions **25***a*, **25***b*.

Another feature of an embodiment of the assembly **10** described above with reference to FIGS. **1**–**3** is that the actuator **50** is in a liquid or otherwise flowable state when it is in motion, and can be solidified when at rest. An advantage of this feature is that the actuator **50** can require less force than some conventional actuators to move between positions because of the relatively low friction between the liquid actuator **50** and the surfaces of the channel **20**. Another advantage is that the actuator **50** may be less susceptible to accidental actuation (for example, in a high pressure or high acceleration environment) because the actuator **50** will not move unless it is heated. Still another advantage is that the actuator **50** can form a strong, liquid-tight and/or gas-tight bond with the surfaces of the channel **20** (generally similar to the bond between solder and soldered wires) when the actuator **50** is in the solid state. Accordingly, the actuator **50** can withstand high pressures when in the solid state.

Still another advantage of an embodiment of the actuator **50** is that the surface tension and the volume free energy of the actuator act to minimize the length of the actuator **50** and preserve the integrity of the actuator when the actuator is in a liquid state. Accordingly, the actuator **50** can withstand relatively high pressures (such as the pressure of the fluid acting or the actuator **50** through the entrance orifice **31**) without becoming fragmented, even when the actuator is in a liquified or partially liquified state.

Yet another feature of an embodiment of the assembly **10** is that the actuator **50** can perform functions other than the valve functions described above with reference to FIGS. **1**–**3**. For example, in one embodiment, the heaters **41** and **42** can be eliminated and the actuator **50** can move when the temperature of its environment increases by an amount sufficient to liquify the actuator **50** and release gas from one of the gas sources **40**. Accordingly, the actuator **50** can be coupled to a fire suppression system or other heat-activated device. In other embodiments, the actuator **50** can be operatively coupled to elements other than a fluid channel, such as electrical contacts of a fuse or a relay to transmit linear motion to the other elements. In other embodiments, the actuator **50** can have other functions and/or can be operatively coupled to other devices.

FIG. **4** is a top isometric view of a portion of an assembly **110** having an actuator **150** configured in accordance with another embodiment of the invention. In one aspect of this embodiment, the assembly **110** can include a body **111** having a first portion **111***a* with a channel **120** and a second portion **111***b* generally similar to the first portion **11***a* and second portion **11***b* described above with reference to FIGS. **1**–**3**B. The actuator **150** is disposed in the channel **120** and is movable within the channel (as indicated by arrows "C" and "D") between a first position (shown in FIG. **4**) and a second position. In the first position, the actuator **150** allows a fluid to pass through a fluid passageway **130** from an entrance orifice **131** across the channel **120** to an exit orifice **132**. In the second position, the actuator **150** blocks the motion of fluid from the entrance orifice **131** to the exit orifice **132**, as will be described in greater detail below.

In one embodiment, the actuator **150** includes two flowable portions **151** positioned at opposite ends of a non-flowable slider portion **152**. The flowable portions **151** operate in a manner generally similar to that described above with reference to FIGS. **1**–**3** to liquify and move the actuator **150** over a wetted region **124** of the channel **120** positioned between a first unwetted region **125***a* and a second unwetted region **125***b*. Conversely, the slider portion **152** can remain in a solid state throughout the operation of the actuator **150** in one embodiment.

In one aspect of this embodiment, the slider portion **152** includes a groove **158** that extends across the width "W" of the channel **120**. The groove **158** is aligned with the entrance orifice **131** and the exit orifice **132** when the actuator **150** is in the open position to allow fluid to pass from the entrance orifice **131** to the exit orifice **132**. The groove **158** is offset from the entrance orifice **131** and the exit orifice **132** when the actuator **150** is in the closed position to prevent the fluid from passing from the entrance orifice **131** to the exit orifice **132**. As the slider portion **152** moves back and forth between the open and closed positions, the flowable portions **151** of the actuator **150** can seal against the surfaces of the channel **120** and the slider portion **152** to prevent the fluid from escaping past the actuator **150** toward opposite ends **126** and **127** of the channel **120**.

In one embodiment, the slider portion **152** can be formed from a hydrogenated amorphous silicon carbide. In one aspect of this embodiment, the slider portion **152** can be formed by depositing in the channel **120** an Si_xC_y:H compound by plasma enhanced chemical vapor deposition (PECVD). The adhesive forces between the resulting slider portion **152** and the surfaces of the channel **120** can be reduced in one embodiment by lowering the temperature at which the PECVD process occurs and/or by adding CF_4 to the plasma to form a $Si_xC_yF_z$:H film. The resulting carbide slider portion **152** can be mechanically polished to produce a flat surface for mating with a top surface **123** of the channel **120** defined by the second portion of the body **111**. The groove **158** can be formed in the slider portion **152** by a reactive ion etching process, which can also be used to remove any extraneous carbide in the channel **120**. In other embodiments, the slider portion **152** can be formed from other materials and/or by other processes.

One feature of an embodiment of the assembly **110** described above with reference to FIG. **4** is that the slider portions **152** can isolate the fluid passing through the passage **130** from contact with the flowable portions **151**. An advantage of this feature is that the assembly **110** can be used to control the flow of fluids that are not compatible with the materials forming the flowable portions **151** of the actuator **150**. Another advantage of this feature is that the slider portion **152** can isolate the fluid in the passageway **130** from contact with the wetted region **124** of the channel **120**. Accordingly, the assembly **110** can reduce the likelihood for oxidizing or otherwise contaminating the wetted region **124**.

FIG. **5** is a schematic illustration of a valve assembly **280** configured to incrementally vary a flow of fluid in accordance with another embodiment of the invention. In one aspect of this embodiment, the valve assembly **280** can include four multiplexed valves **210** (shown as valves **210***a*–**210***d*), each configured in a manner generally similar to the assembly **10** or the assembly **110** described above with reference to FIGS. **1**–**4**. Accordingly, each valve **210** has a entrance orifice **231**, an exit orifice **232**, and an actuator (not shown in FIG. **5**) that can move back and forth between the entrance orifice **231** and the exit orifice **232** to open and close fluid communication between each pair of entrance and exit orifices. In a further aspect of this embodiment, each valve **210** can have a separate gas source for driving each valve actuator. Alternatively, a pair of gas sources (one for each direction of travel of the actuators) can be coupled to all the valves **210***a*–**210***d*, with only selected valve actuators moving, depending on which actuator heaters are activated.

In a further aspect of this embodiment, each entrance orifice **231** can be coupled to an entrance manifold **282** which is in turn coupled to a source **284** of fluid. Each exit orifice **232** can be coupled to an exit manifold **283** which can in turn be coupled to downstream devices (not shown). Alternatively, the valves **210***a*–**210***d* can be coupled to different sources **284**, for example, to mix fluids from the different sources.

In still another aspect of this embodiment, each valve **210** can have a different flow capacity. For example, the first valve **210***a* can have a flow capacity of one flow rate unit, the second valve **210***b* can have a flow capacity of two flow rate units, the third valve **210***c* can have a flow capacity of three flow rate units, and the fourth valve **210***d* can have a capacity of four flow rate units. By selectively opening one or more of the valves **210***a*–**210***d*, the valve assembly **280** can allow a fluid flow having any integer value of from zero flow rate units to **10** flow rate units to pass from the entrance manifold **282** to the exit manifold **283**. Accordingly, while each individual valve **210** does not incrementally adjust the flow of fluid from the entrance manifold **282** to the exit manifold **283**, the combination of valves **210** can provide such an incremental adjustment. In other embodiments, other combinations of valves and valve capacities can be used to provide more or fewer incremental flow rates. In one embodiment, the valves **210***a*–**210***d* can be formed in a single substrate (such as a semiconductor substrate) or alternatively, one or more of the valves **210***a*–**210***d* can be formed in a separate substrate.

From the foregoing, it will be appreciated that specific embodiments of the invention have been described herein for purposes of illustration, but that various modifications may be made without deviating from the spirit and scope of the invention. Accordingly, the invention is not limited expect as by the appended claims.

What is claimed is:

1. A method for controlling an actuator, comprising:

heating the actuator in an actuator channel from a solid state to a flowable state;

moving the actuator within the actuator channel from a first position to a second position with a flowable portion of the actuator in contact with surfaces of the actuator channel, the flowable portion of the actuator having a first surface tension when adjacent to the first position in the actuator channel and a second surface tension greater than the first surface tension when adjacent to the second position in the actuator channel;

cooling the actuator to solidify the actuator in the second position; and

moving the actuator from the second position to the first position.

2. The method of claim **1** further comprising liquifying the actuator before moving the actuator from the first position to the second position.

3. The method of claim **1**, further comprising covering an orifice to at least restrict a flow of fluid through the orifice by moving the actuator from the first position to the second position.

4. The method of claim **1** wherein moving the actuator includes applying pressurized gas to the actuator.

5. The method of claim **1** wherein moving the actuator includes:

heating a first hydride material to release hydrogen into the actuator channel on a first side of the actuator to drive the actuator in a first direction;

heating a second hydride material to release hydrogen into the actuator channel on a second side of the actuator to drive the actuator in a second direction opposite the first direction; and

cooling at least one of the first and second hydride materials to reabsorb at least some of the hydrogen.

6. The method of claim **1** wherein heating the actuator includes heating a portion of the actuator that includes at least one of lead, tin, bismuth, cadmium, selenium, thallium and zinc.

7. The method of claim **1** wherein moving the actuator includes moving the actuator over a surface that includes at least one of platinum, rhodium, palladium and gold.

8. The method of claim **1** wherein moving the actuator from the first position to the second position includes halting motion of the actuator at the second position by engaging the actuator with at least one of an oxide surface and a nitride surface.

9. The method of claim **1** wherein moving the actuator from the second position to the first position includes reheating the actuator in the actuator channel from a solid state to a flowable state, and moving the actuator within the actuator channel from the second position to the first position with a flowable portion of the actuator in contact with surfaces of the actuator channel.

10. A method for controlling an actuator, comprising:

heating the actuator in an actuator channel from a solid state to a flowable state;

moving the actuator within the actuator channel from a first position to a second position with a flowable portion of the actuator in contact with surfaces of the actuator channel, wherein moving the actuator includes applying pressurized gas to the flowable portion of the actuator; and

cooling the actuator to solidify the actuator in the second position.

11. A method for controlling an actuator, comprising:

heating the actuator in an actuator channel from a solid state to a flowable state;

moving the actuator within the actuator channel from a first position to a second position with a flowable portion of the actuator in contact with surfaces of the actuator channel, wherein moving the actuator includes:

heating a first hydride material to release hydrogen into the actuator channel against a first side of the flowable portion of the actuator to drive the actuator in a first direction;

heating a second hydride material to release hydrogen into the actuator channel against a second side of the flowable portion of the actuator to drive the actuator in a second direction opposite the first direction; and

cooling at least one of the first and second hydride materials to reabsorb at least some of the hydrogen; and

cooling the actuator to solidify the actuator in the second position.

12. A method for controlling an actuator, comprising:

heating the actuator in an actuator channel from a solid state to a flowable state, wherein heating the actuator includes heating a portion of the actuator that includes at least one of lead, tin, bismuth, cadmium, selenium, thallium and zinc;

moving the actuator within the actuator channel from a first position to a second position with a flowable portion of the actuator in contact with surfaces of the actuator channel, the flowable portion of the actuator having a first surface tension when at the first position in the actuator channel and a second surface tension greater than the first surface tension when adjacent to the second position in the actuator channel; and

cooling the actuator to solidify the actuator in the second position.

13. A method for controlling an actuator, comprising:

heating the actuator in an actuator channel from a solid state to a flowable state;

moving the actuator within the actuator channel from a first position to a second position with a flowable portion of the actuator in contact with surfaces of the actuator channel, wherein moving the actuator includes applying pressurized gas to the flowable portion of the actuator to move the actuator over a surface that includes at least one of platinum, rhodium, palladium and gold; and

cooling the actuator to solidify the actuator in the second position.

14. A method for controlling an actuator, comprising:

heating the actuator in an actuator channel from a solid state to a flowable state;

moving the actuator within the actuator channel from a first position to a second position with a flowable portion of the actuator in contact with surfaces of the actuator channel, wherein moving the actuator from the first position to the second position includes halting motion of the actuator at the second position by engaging the actuator with at least one of an oxide surface and a nitride surface; and

cooling the actuator to solidify the actuator in the second position.

15. A method for controlling an actuator, comprising:

liquefying the actuator in an actuator channel by heating the actuator;

heating a hydride source to release hydrogen gas into the actuator channel;

driving the hydrogen gas against the liquefied actuator to move the liquefied actuator within a first region of the actuator channel from a first position toward a second position, the liquefied actuator having a first surface tension when in the first region of the actuator channel;

halting motion of the liquefied actuator within the actuator channel by engaging the liquefied actuator with a second region of the actuator channel, the liquefied actuator having a second surface tension greater than the first surface tension adjacent to the second region of the actuator channel; and

solidifying the liquefied actuator in the second position by cooling the actuator.

16. The method of claim **15**, further comprising moving the actuator back and forth between the first position and the second position at a rate of up to at least 1,000 cycles per second.

17. The method of claim **15** wherein heating a hydride source includes heating a first hydride source to release hydrogen gas into the actuator channel on a first side of the liquefied actuator to move the liquefied actuator in a first direction, and further comprising heating a second hydride source to release hydrogen gas into the actuator channel on a second side of the actuator to move the liquefied actuator in a second direction opposite the first direction.

18. The method of claim **15** wherein heating a hydride source includes heating a first hydride source to release hydrogen gas into the actuator channel on a first side of the liquefied actuator to move the liquefied actuator in a first direction, and further comprising:

heating a second hydride source to release hydrogen gas into the actuator channel on a second side of the actuator to move the liquefied actuator in a second direction opposite the first direction; and

cooling at least one of the first and second hydride sources to reabsorb at least some of the hydrogen.

19. The method of claim **15**, further comprising covering an orifice to at least restrict a flow of fluid through the orifice by moving the actuator from the first position to the second position.

20. The method of claim **15** wherein liquefying the actuator includes heating a portion of the actuator that includes at least one of lead, tin, bismuth, cadmium, selenium, thallium and zinc.

21. The method of claim **15**, wherein moving the actuator includes moving the actuator over a surface that includes at least one of platinum, rhodium, palladium and gold.

22. The method of claim **15** wherein halting motion of the liquefied actuator at the second position includes engaging the liquefied actuator with at least one of an oxide surface and a nitride surface.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,935,355 B2
DATED : August 30, 2005
INVENTOR(S) : Eldridge

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 3,
Line 27, "the side is surfaces" should be -- the side surfaces --.

Signed and Sealed this

Twenty-seventh Day of December, 2005

JON W. DUDAS
Director of the United States Patent and Trademark Office